Reprinted from *J. Food Sci.*
45(5):1318-1320 & 1326

EVALUATION OF THE COMPRESSIVE DEFORMABILITY MODULUS OF FRESH AND COOKED FISH FLESH

E. A. JOHNSON, R. A. SEGARS, J. G. KAPSALIS,
M. D. NORMAND, and M. PELEG

ABSTRACT

Specimens of fresh and cooked fish fillets of a variety of species were compressed by an Instron Universal Testing Machine. The output, converted to true stress-strain relationships, revealed an initial linear portion up to 20–40% strain. This enabled the calculation of the modulus of deformability from the slope. The curve continuation was concave upwards in raw specimens, most likely because of the development of hydrostatic pressure. In cooked specimens the continuation was mostly concave downward, possibly an indication of structural disintegration. Variations in the calculated moduli were large along the same fillets and among fillets of the same species.

INTRODUCTION

OBJECTIVE EVALUATION of fish texture is difficult. The nonuniformity of the structure is reflected on both the small scale (e.g. flakiness) and the large scale (e.g. variations along the fish body). Furthermore, since a fish, even after filleting, maintains size and unique shape characteristics, it is extremely hard to prepare specimens of standard dimensions for mechanical testing. In such cases, even the possibility of accurate mapping of textural differences becomes questionable and consequently any comparison between species or individual fish.

A well known way to reduce the mechanical artifacts due to the specimen dimensions in uniaxial deformation is by transformation of the force-time (or force displacement) relationships recorded by Universal testing machines into true stress-strain relationships (Marin, 1962). Though this type of representation does not account for diameter related effects (Lindley, 1979) nor instrumental artifacts such as those generated by the recorder response time (Voisey and Kloeck, 1975) or by friction along the supporting surfaces (Marin, 1962; Culioli and Sherman, 1976), it can still show gross inherent differences among materials that cannot be revealed by curves plotted in apparent coordinates (Calzada and Peleg, 1978).

In this work, the possibility of measuring a compressive deformability modulus, based on true stress-strain relationships has been studied and evaluated. The term "modulus of deformability" suggested by Mohsenin and Mittal (1977) is a replacement of Young's modulus which is only applicable to small elastic strains. The deformability modulus is representative of a material's overall resistance to deformation. The latter may include irreversible and rate dependent deformations, both small and large. Unlike Young's modulus, the actual measured value of the deformability modulus must depend on the test conditions, especially on the specimen dimensions (Lindley, 1979) and the deformation rate (Peleg, 1977). However, if these effects within a certain experimental range are secondary in magnitude, such a modulus may be a useful, practical parameter in the mechanical characterization of food materials.

Authors Johnson, Normand, and Peleg are with the Dept. of Food Engineering, Agricultural Engineering Building, Univ. of Massachusetts, Amherst, MA 01003. Authors Segars and Kapsalis are with the U.S. Army Natick Laboratories, Natick, MA 01760.

0022-1147/80/0005-1318$02.25/0

Apparent and true coordinates and the modulus of deformability

The differences between the force-deformation curve and the true stress-strain curves are shown in Figure 1. The shape of the force-deformation curve and consequently that of the apparent stress-strain relationship is typically concave upward almost up to failure (e.g. up to 30–40% deformation in fresh fish). This typical shape characteristic is mainly determined by the progressive expansion of the cross-sectional area. Therefore, the curves of a large variety of materials appear similar in shape, a factor that masks their real mechanical properties. Furthermore, in practice, especially when specimens of biological materials are prepared for uniaxial deformation, the ends of the specimens are not perfectly parallel or smooth. This adds an initial (and additional) curvature to the force deformation curves. This artifact can easily be corrected when the material is tough and has a relatively steep force-deformation curve. It is not so in soft materials where the curvature attributed to this factor is comparable to that of the curve itself.

Calculation of the modulus

The modulus of deformability M (Fig. 1b) is defined as:

$$M = \frac{\sigma_T}{\epsilon_T} \tag{1}$$

where σ_T and σ_T are the true stress and strain respectively.

For an incompressible material and with the assumption that the specimen retains its shape during deformation:

$$\sigma_T = \frac{F(t)}{A(t)} = \frac{F(t)\,[H_o - \Delta H]}{A_o\,H_o} \tag{2}$$

where F(t) is the force, A(t) the actual cross-sectional area, A_o and H_o are the original cross-sectional area and height of the undeformed specimen and ΔH the absolute deformation.

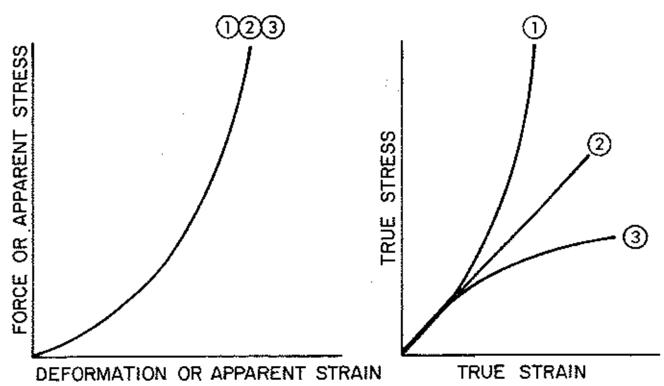

Fig. 1—Schematic representation of the difference between apparent and true compressive stress-strain relationships.

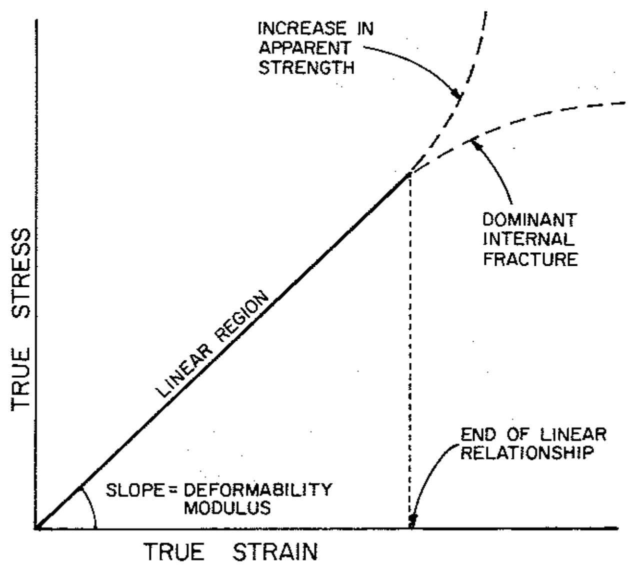

Fig. 2—Mechanical characterization of fish flesh by true stress-strain curves.

The true compressive strain under these conditions is:

$$\epsilon_T = \ln \left(\frac{H_o}{H_o - \Delta H} \right) \tag{3}$$

Though these parameters, as already mentioned, do not account for local conditions in the specimen, they can be and are used as a means of general interpretation of data obtained in uniaxial deformation tests (Marin, 1962).

MATERIALS & METHODS

REFRIGERATED FILLETS of a variety of fish species were brought to the laboratory within 24 hr after commercial filleting. Some of the fillets were cooked in plastic bags, submerged in a hot water bath, with circulating water at a temperature of 69°C. The process was stopped when the center temperature reached 65°C. The required cooking time was 6–35 min depending on the thickness of the fillet. The samples were then removed from the bath and left to cool at ambient temperature.

Hundreds of specimens of both raw and cooked fillets were carefully cut using an electric carving knife. During cutting the surrounding tissues were held in place by a device constructed of a dense array of needles which guided the knife and at the same time prevented the disintegration of the outer wall of the specimen. The specimens were always cut in a direction perpendicular to the fillet plane regardless of the local orientation of the flakes.

The dimensions of each specimen (about 15 cm² of cross-sectional area and 1.5–3 cm in height) were determined by a caliper prior to the deformation test. The latter was performed by an Instron Universal Testing Machine equipped to provide force deformation output in a digital form. The data were converted by a computer program to true stress-strain relationships as described in Eq (2) and (3). The deformability modulus was calculated from the linear portion of the relationship which was also analyzed statistically for the determination of the regression coefficient.

RESULTS & DISCUSSION

Shape of the stress-strain curve

Schematic representation of prefailure stress relationships of a variety of fish species are shown in Figure 2. The figure demonstrates that up to a certain strain, usually in the range 20–40%, the relationship was linear, supported by correlation coefficients of 0.95–0.99 as shown in Tables 1–4. This enables the calculation of the deformability modulus from the slope of the straight line for each individual specimen. Another objective textural parameter, so derived, is the strain range in which the linear relationship holds.

Additional characteristics of the material mechanical properties is the shape of the curve continuation. A concave upward shape (i.e. the slope increases) can indicate compressibility, development of hydrostatic pressure or the existence of other mechanisms that contribute to increase in apparent strength. A concave downward shape (i.e. the slope decreases) on the contrary, is a clear indication of internal fracture and structural disintegration of the deformed specimen (Calzada and Peleg, 1978).

Mechanical properties of fish flesh

Typical values of deformability moduli of the flesh of a variety of fish species are given in Tables 1–4. These reflect great variability in magnitude which is an indication of textural nonuniformity of the flesh. It could be expected that specimens taken from the rear part of the fillets, i.e. closer to the tail, would show significantly tougher properties. This however can hardly be revealed when a small number of specimens are tested. One of the reasons for that is the great probability that part of the fish has suffered irreversible deformation during the filleting process. It can also be argued that the inevitable differences in the temperature history of the different specimens (within and among the tested species) are responsible, at least partly, to the vari-

Table 1—Mechanical characteristics of Hake (Urophycis tenuis) fish fillets

Fish	Specimen location	Upper limit of linear $\sigma = \sigma(\epsilon)$[a] (% strain)	Regression coefficient r	Deformability modulus[a] (N cm^{-2})	Slope of $\sigma = \sigma(\epsilon)$ curve continuation beyond linear region[a]
	front	20–25	0.97**	3.1	increases
raw	middle	25	0.96**	1.7	increases
	rear	25	0.96**	1.7	increases
	front	20–25	0.97**	3.8	increases
raw	middle	20	0.98**	2.3	increases
	rear	20	0.97**	3.8	increases
	front	20–25	0.99**	2.7	decreases
cooked	middle	25–30	0.99**	2.5	decreases
	rear	20–25	0.99**	2.5	decreases
	front	20	0.98**	3.9	decreases
cooked	middle	25	0.99**	4.0	decreases
	rear	25–30	0.99**	5.1	decreases

[a] See Fig. 2.
* Significant at 0.05 level; **Significant at 0.01 level.

ability discovered among cooked fillets. Generally however, the softening effect of cooking was measurable in terms of the deformability modulus. (Overcooking, not reported in this paper, will cause disintegration of the specimen and will eventually reduce the modulus to zero).

One significant characteristic of cooked specimens was the shape of the stress-strain curves. While all the raw samples, beyond the linear region (Fig. 2) had a concave upward shape, most of the cooked specimens had a concave downward continuation. (In the exceptional specimens the slope increase was extremely small). The difference lies in the physical difference between fresh and cooked fillets. In the former, the considerable liquid content enabled the development of hydrostatic pressure during compression. Much of the liquid has been lost during cooking, thus leaving a structure that basically consisted of denatured muscle tissue.

CONCLUSIONS

A METHOD of interpretation of fish flesh stress-strain data has been described. The evidence suggests that the modulus of deformability as well as the shape characteristics of the true stress-strain relationship can be sensitive indices to textural properties and reveal differences along the fish fillets as well as between individual fillets, and species in both fresh and cooked forms.

—Continued on page 1326

Table 2—Mechanical characteristics of pollock (Pollachius virens) fish fillets

Fish	Specimen location	Upper limit of linear $\sigma = \sigma(\epsilon)$[a] (% strain)	Regression coefficient r	Deformability modulus[a] (N cm^{-2})	Slope of $\sigma = \sigma(\epsilon)$ curve continuation beyond linear region[a]
	front	20–25	0.97**	5.1	increases
raw	middle	20–25	0.95**	2.0	increases
	rear	25	0.98**	5.4	increases
	front	20–25	0.98**	3.9	increases
raw	middle	25	0.99**	3.3	increases
	rear	25	0.99**	1.5	increases
	front	25	0.99**	2.2	decreases
cooked	middle	25–30	0.97**	2.4	decreases
	rear	50	0.99**	2.2	sl increase
	front	20–25	0.96**	4.6	decreases
cooked	middle	20–25	0.99**	2.6	decreases
	rear	20–25	0.99**	3.9	decreases

[a] See Fig. 2.
* Significant at 0.05 level; **Significant at 0.01 level.

Table 3—Mechanical characteristics of flounder (Pseudopleuronecetes americanus) fish fillets

Fish	Specimen location	Upper limit of linear $\sigma = \sigma(\epsilon)$[a] (% strain)	Regression coefficient r	Deformability modulus[a] (N cm^{-2})	Slope of $\sigma = \sigma(\epsilon)$ curve continuation beyond linear region[a]
	front	25–30	0.96**	1.5	increases
raw	middle	25–30	0.98**	8.8	increases
	rear	30–35	0.99**	8.4	increases
	front	40	0.99**	2.9	sl. increase
cooked	middle	40	0.98**	2.8	sl. increase
	rear	50	0.99**	4.4	sl. increase

[a] See Fig. 2.
* Significant at 0.05 level; **Significant at 0.01 level.

Table 4—Mechanical characteristics of miscellaneous fish fillets.

Species	Specimen raw/cooked	Upper limit of linear $\sigma = \sigma(\epsilon)$[a] (% strain)	Regression coefficient r	Deformability modulus[a] (N cm^{-2})	Slope of $\sigma = \sigma(\epsilon)$ curve continuation beyond linear region[a]
Bluefish	Raw	25	0.95*	1.6	increases
(Potatomus					
soltatrix)	Cooked	25	0.99**	1.8	decreases
Cod	Raw	25–30	0.97**	7.3	increases
Godus morhua)					
	Cooked	25	0.99**	2.5	sl increase
Wolf	Raw	25	0.96**	6.0	increases
(Anarhichas					
lupus)	Cooked	25	0.99**	1.9	decreases

[a] See Fig. 2.
* Significant at 0.05 level; **Significant at 0.01 level.

Since the objective of the work was the development of a procedure and not the study of actual differences between commercially available fillets, no effort has been made to characterize or quantify these differences. It has become clear however, from the data already gathered, that variations between locations and fillets of the same species are large. This may be due to geographical, seasonal, and feeding factors related to the live fish, the orientation of the flakes within the specimen, and to postmortem biochemical factors and the filleting process itself. (Love, 1975; Howgate, 1977).

REFERENCES

Calzada, J.F. and Peleg, M. 1978. Mechanical interpretation of compressive stress-strain relationship of solid foods. J. Food Sci. 43: 1087.

Culioli, J. and Sherman, P. 1976. Evaluation of Gouda cheese firmness by compression tests. J. Texture Studies 7: 353.

Howgate, P. 1977. Aspects of fish texture. In "Sensory Properties of Foods," Ed. D.S. Burch. Applied Science Publ. Ltd., England.

Lindley, P.B. 1979. Compression moduli for blocks of soft elastic material bonded to rigid end plates. J. Strain Analysis 14: 11.

Love, M.R. 1975. Variability in Atlantic Cod from the northeast Atlantic: A Review of seasonal and environmental influences on various attributes of the flesh. J. Fisheries Research Board of Canada 32(12): 2333.

Marin, J. 1962. "Mechanical Behavior of Engineering Materials." Prentice Hall, Inc., New Jersey.

Mohsenin, N.N. and Mittal, J.P. 1977. Use of rheological terms and correlation of compatible measurements in food texture research. J. Texture Studies 8: 395.

Peleg, M. 1977. Operational conditions and the stress-strain relationships of solid foods. J. Texture Studies 8: 283.

Voisey, P.W. and Kloek, M. 1975. Instron recorder pen response. J. Texture Studies 6: 375.

Ms received 11/10/79; revised 2/9/80; accepted 2/12/80.

This work has been supported by the U.S. Department of Commerce, National Marine Fisheries Service, under Interagency Transfer Act Contract No. 01-8-MO1-6320.